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HABITABILITY: CAMELOT IV

UNIVERSITY OF PUERTO RICO
SCHOOL OF ARCHITECTURE

INTRODUCTION

Fifty years after the start of the Space Exploration Initiative there will be a permanent martian outpost in operation. Transporting personnel to it will be accomplished by sending passengers through a shuttle to a vehicle in a heliocentric elliptical orbit intersecting both Earth's and Mars' orbits, while it is in terrestrial proximity. Passengers will land on Mars a month and a half later through a transfer shuttle that will also exchange Earth-bound passengers to the vehicle reaching perigee again in 22 months.

Such a vehicle was originally conceived at the Aerospace Engineering Department of the University of Michigan in 1987 as part of the NASA/USRA Advanced Design Program. It was called CAMELOT, an acronym for Circulating Autosufficient Mars-Earth Luxurious Orbital Transport. It housed 17 passengers and a crew of 3 in a 3.6 m × 7.3 m rectangular cross-section toroid of 34.1 m radius, thus providing a volume of 284.8 m^3 per person, including the Closed Environmental Life Support System (CELSS). It created an artificial gravity of 0.4 *g* by rotating the ring at a rate of 3.22 rpm.

During 1988-89 the NASA/USRA Advanced Design Program sponsored research and design efforts at the School of Architecture of the University of Puerto Rico aimed at developing habitability criteria and at defining a habitability concept as a useful tool in understanding and evaluating dwellings for prolonged stay in extraterrestrial space. CAMELOT was studied as a case in which the students would try to enhance the quality of life of the inhabitants by applying architectural design methodology. Thus, a process of transformation of the original CAMELOT took place and the CAMELOT III presented to NASA/USRA's Advanced Design Program evolved.

HABITABILITY CONCEPT DEFINITION

The study proposed 14 habitability criteria considered necessary to fulfill the defined habitability concept, which is "that state of equilibrium that results from the interaction between components of the Individual Architecture Mission Complex, which allows a person to sustain physiological homeostasis, adequate performance, and acceptable social relationships."

The habitability criteria can be summarized as follows:

1. Personal Indentification: Refers to the possibility of allowing the individual to influence the arrangement of his/her personal areas.
2. Social Interaction: To satisfy the need for companionship.
3. Aleatoric Conditions: To avoid excessive routine, providing pleasant surprises.
4. Contact with Nature: Is a buffer to soften the impact of a totally encompassing artificial environment and developing a new sense of indoor-outdoor.
5. Mental Landscapes: To evoke memories, symbols, and experiences of terrestrial life.
6. Privacy: A private place for everyone on prolonged stay in an enclosed habitation is necessary to maintain harmony in interpersonal relationships and self-reliance.
7. Equalitarian Conditions: Differences among passenger facilities should reflect purpose and function, as well as individual preferences, rather than rank or hierarchy.
8. Variability: Environmental stress can be overcome by introducing a variety of elements, shapes, decor, color, materials, and textures.
9. Functionality: A "habitable" place must perform well in the physiological-quantitative sense for the sustenance of human life beyond the level of mere survival.
10. Sensorial Stimulation: Cognitive processes depend on all senses; therefore, visual stimuli are to be complemented by an environment rich in positive auditory, tactile, olfactory, and gustatory factors and enhancements.
11. Music and Environmental Sound: The problem of absolute silence in extraterrestrial space has to be dealt with to prevent travelers from being startled by their own visceral motions and by any minor unexpected noise, as well as to control access to communications.
12. Stability and Security: Muscle tone and visual-motor coordination developed under terrestrial conditions will find alien an environment where there are gravity gradients, Coriolis and gyroscopic forces, and constant torque on the anatomy. The environment must be designed to compensate for these conditions.
13. Comfort: Includes conditions such as illumination, temperature, humidity, pressure, and atmospheric composition, which can be quantitatively determined according to standards.
14. Sense of Orientation: The architectural design of floors, walls, and ceilings must create a new sense of up and down, east and west, north and south to reinforce orientation.

ARCHITECTURAL DESIGN DEVELOPMENT

A series of design factors and architectural strategies were considered in making the following changes to the original CAMELOT:

1. The single-level toroid ring of a 12′ × 24′ cross-section was changed to a two-level, true torus of 24′ section diameter, keeping the 112′ rotational radius.

2. Consequently, the volume increased by 41% to allow for quality of life enhancements.

3. The CELSS was reorganized by moving it to the lower level of the torus, which is also its outer level, and was compartmentalized in a system of drawers that ran along the sides of the main corridor of the vessel, providing for circumferential access and transportation.

4. The areas of the vessel were reorganized into three main sectors (instead of four), thus using only three spoke elevators to provide access to and from the central core. The areas were organized as the dwelling sector, which includes cabins for passengers and crew members; the work sector, which includes laboratories, torus control room, medical center, and a master CELSS; and the leisure sector, including a galley, dining-conference room, library-lounge, recreation-gymnasium, and a chapel.

5. Additionally, the three spoke elevators were placed in a lobby, under which the safe havens were located, containing facilities for dwelling while the vessel is under the influence of extreme radiation because of solar flare activity or some other hazardous condition that would require such protection. The Safe Havens consist of a series of cubicles measuring 8′ × 4′ × 4′ high that are highly shielded, have food supplies for at least 24 hr, allow access to communications, computers, and entertainment, and contain supplies for clothing changes, a personal toilet, and a couch for sleeping or sitting.

6. The circumferential corridor provided a continuous means of circulation along the lower level of the entire torus, flanked on one side by a carousel-type transport for cargo or injured humans, and a means of reaching every room in the vessel. Access to rooms was always through vertical ladders and hatches on the ceiling to promote upper body tonification by requiring its use for locomotion.

7. Interior gardens were provided as an external CELSS feature in several two-story locations along the dwelling and leisure sectors.

REFINEMENTS AND REVISIONS TO IMPROVE QUALITY OF LIFE

Considering that several of the habitability criteria were dependent on qualitative, rather than quantitative factors, it was deemed necessary to develop them further in order to ensure and promote greater objectivity in evaluating habitats for prolonged stay in extraterrestrial space. CAMELOT III was also found underdesigned as far as (1) the nature of the enveloping membrane, which was required to withstand pressures of 2000 lb per sq ft to hold the required internal atmosphere of the vessel; (2) the assembly process in Earth orbit for such a vessel (robotics and EVA processes); (3) the security systems for emergency and accidental conditions of operation; (4) the need for a detailed example of lighting, texture, materials, and color scheme to illustrate the application of the habitability criteria; and (5) the design of its furniture, which was found to be still too prejudiced by 1-*g* living conditions.

These provided the working agenda for the Space Research and Design Studio during academic year 1989-90.

NEW INSIGHTS ON ARTIFICIAL GRAVITY

From the available data, it soon became evident that artificial gravity is necessary to overcome physiological and even anatomical deterioration of humans on prolonged stay in space. During research, however, further insight was gained regarding the architectural implications of such artificial gravity in environments, disclosing conditions such as (1) Coriolis and gyroscopic effects over all bodies in motion (north-south movements), which are 4000 times greater than those experienced on the surface of Earth; (2) weight gains and losses related to east-west movements of significant magnitude due to the addition or subtraction to the circumferential speed, which causes the centripetal force that creates the artificial gravity effect; (3) gravitational gradients due to upward and downward movements (toward or away from the center of rotation movements); in fact, due to the conditions of CAMELOT, the person who would experience 0.4 *g* on his/her feet, would also be experiencing 0.37 *g* on the top of his/her head; (4) discomfort due to dislocation of reflexes relating to normal visual input and its correlative input from the inner-ear fluid motion. (In the September 1962 issue of *Astronautics*, a chart was published relating the rotational parameters to a comfort zone for the design of artificial gravity manned space stations. CAMELOT was designed taking into account such parameters. However, more recent research has made corrections in relation to the rotational parameters, leaving CAMELOT just outside the comfort zone.); (5) excessive variations in local verticals that create confusion and disorientation; (6) unfamiliar behavior of objects and bodies that tend to move in straight paths, while the environment or the frame of reference is rotating. (It is conceivable that in CAMELOT a body suspended unrestrained for one second would not only experience a lateral displacement due to inertia, but could also rotate up to 58° relative to the envelope); and (7) large anatomical stresses as a consequence of such rotational and lateral displacements. For example, if the passenger were to rely on feet and balance alone to stand erect, assuming he/she has become accustomed to the moving environment, the torque exerted by the gluteous maximus over the trocanter bone in the sagittal plane would be 700 times that of normal anatomical stresses.

FORM AND CONSTRUCTION PROBLEMS

Additionally, construction and form difficulties were found, such as

1. Large periods of time and numbers of people will be needed for extravehicular activity (EVA) in low Earth orbit (LEO) for the assembly of the skin of the vessel.

2. It will be difficult to attain air tightness in the membrane assembled in orbit due to the great number of joints.

3. Due to fluctuations in the upper atmosphere, orbit decay is an ever-present danger during LEO assembly until the vessel has attained enough structural integrity to make orbital corrections possible.

4. A relatively small torus like CAMELOT (112′ radius), cannot fulfill the promise of spatial continuity because floors curve up too steeply and are perceived as walls at a distance. Ceilings bend away in horizons, which seem to meet the floors, to visually enclose the volume, thus making it impossible to view really large expanses of areas.

5. The monolithic integrity of the toroidal form does not lend itself to the modular redundancy principle aimed at providing subsistence in case of failure of life support systems, fire, decompression, puncture of the membrane, fracture of the structure, or any other similar emergency or accident.

6. Extreme limitation of the capacity for passengers, while requiring 14,000 ft^3 of volume per passenger (including CELSS), makes the vessel too luxurious or uneconomical.

7. The extreme Coriolis and gyroscopic effects on a passenger moving on the hallway, as mentioned before, would require design of handrails and other grab bars to ensure a means of personal locomotion, using the upper body and not only the legs as in terrestrial environments, in order to exert control over such a motion and to relieve the body of extreme anatomical stresses.

8. The period between the warning of solar flare radiation and its actual arrival can be as little as 20 sec. Therefore, Safe Havens cannot be concentrated in a given location, but must be dispersed throughout the vessel, so that they can be reached from any location in such a short time.

A NEW VESSEL, SIMILAR CONCEPT

To solve those problems, a new version, called CAMELOT IV, has been designed. It consists of 12 shuttle external tank (ET) envelopes on an array of 3 groups of 4, tethered from a common core. The passenger capacity has been tripled to 60 persons and therefore its volume has also increased. The array rotates at a 1-km radius (instead of 30 m) at a speed of 0.6 rpm (instead of 3.22 rpm). Thus, gravitational and locomotion conditions become 80-90%, similar to those experienced on Earth. The tether arms are built using Buckminster Fuller's concept of "tensegrity" and are 1 km long with a section 30.38×30.38 m supporting a solar energy collector array of 24,000 m^3. They carry up to four elevators to the microgravity sector in the central hub, which in turn houses laboratories, the nonrotating interface for passengers, supplies, and cargo access. That core also houses the observatory, the command bridge, part of the antenna, and an ejectable nuclear reactor array.

The idea of tensegrity was promoted by R. Buckminster Fuller, the inventor of geodesic geometry, as a means of achieving very versatile, lightweight structures in which the members in compression are minimized and are discontinuous, whereas the members in tension are continuous and very slender, giving the structures an appearance of floatability.

The solar energy collector array was arrived at after consideration of several alternatives. The first one was to place a dish with a radius of 87.4 m around the central core. It was discarded because it required additional structural support. For the same reason, the idea of a 4-m-wide ring at 1 km radius was rejected. The proposed solution of an 8-m-wide strip of solar panels attached along the length of the tensegrity tether arms seemed to be the most practical solution.

The orbital trajectory design developed at Michigan was kept with two new enhancements proposed: (1) the requirement that the main plane of the vessel that contains the solar energy panel array will always be facing towards the Sun; (2) that a 24-hr precession motion be introduced to the axis of rotation to create a sense of daily cycles in the "natural" illumination through ceiling panels and windows. This would help maintain the circadian cycles of crew and passengers as they live on the vessel.

It is envisioned that an antenna array would allow 360° rotation so that some would always be facing Earth base, whereas the others would always be pointing toward the martian base.

Four shuttle liquid hydrogen external tanks have the equivalent volume of the original CAMELOT. Conceivably, they could be recycled and refurbished for use in such a vessel, rather than wasting their sturdy and airtight skin by burning it in the atmosphere, which is the current procedure. It is proposed that they be redesigned so that access be made possible to their interior for construction of habitable quarters in a higher orbit, where they could be stored until the time that NASA is ready to build CAMELOT.

Instead of using counterweights to balance the tethers of CAMELOT IV, it is proposed that the capacity of the vessel be increased in order to subdivide the community in modules similar in size to the original CAMELOT, so that instead of 20 people, there would be 60, or three arrays of four ETs for 20 people each. Each ET envelope will contain its own CELSS. Organization into three sectors, dwelling, work, and leisure, will be conserved to grant a sense of mobility to the passengers, even within their own particular array. Circulation between ETs of one array is accomplished through $12' \times 12'$ cylinder connectors. Transportation between arrays and the central microgravity core is through the four tensegrity tether arm elevators.

The dwelling sector ET array now proposed consists of two ET envelopes (the recycling of a shuttle's liquid hydrogen tank). They would be organized in three floors. Each dwelling ET will house 10 cabins, and a meeting area on the center floor. There will be a torus control room in one of them. Safe havens will be located in the upper level and a CELSS along the lower level corridor.

The work sector will consist of only one ET envelope to be located north of the dwelling sector. It will house four laboratories, a medical center and a master CELSS, all of which will be distributed in the two upper floors. The lower floor will also house a CELSS along the corridor.

The leisure sector ET will also be one tank located south of the dwellings, containing galley, dining-conference room, library-lounge area, a double-height gymnasium-recreation room, and a chapel.

All sectors will have double- and triple-height gardens at the rounded ends of the envelopes. The recycled conical liquid oxygen tanks and the collar connectors of the shuttle ETs could be used for assembling the microgravity laboratories and other facilities in the core.

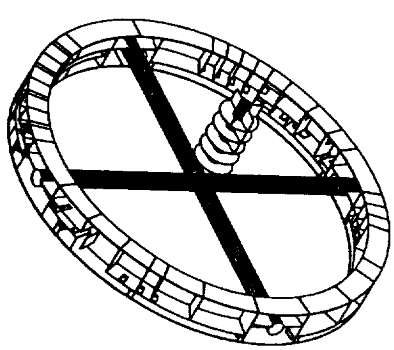
Spoke elevators will consist of 8-ft-diameter cylinders that will travel on cables located within the tensegrity tether structure between the ET arrays and the central core.

THE FINAL CAMELOT

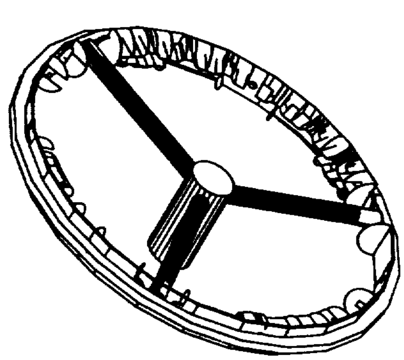
CAMELOT IV is presented here in a tripodal configuration, but conceivably it is a form that allows for growth and expansion. It could be exploded to a multiple-arm array, as long as there is means of counterbalancing the tethers and the spin is controlled to attach additional arms to reach eventual toroidal form of 1 km radius. By that time the start of the Space Exploration Initiative will be a subject of study for historians. CAMELOT would then have 108 arrays of 4 ETs and would be transporting a population of over 2000 people between Mars and Earth, two of the planets inhabited by a multiplanetary human species reaching for the stars.

APPENDIX

Illustrations pertaining to Camelot IV are included in this Appendix.



Camelot I. Axonometric



Camelot II. Axonometric

ACKNOWLEDGMENTS

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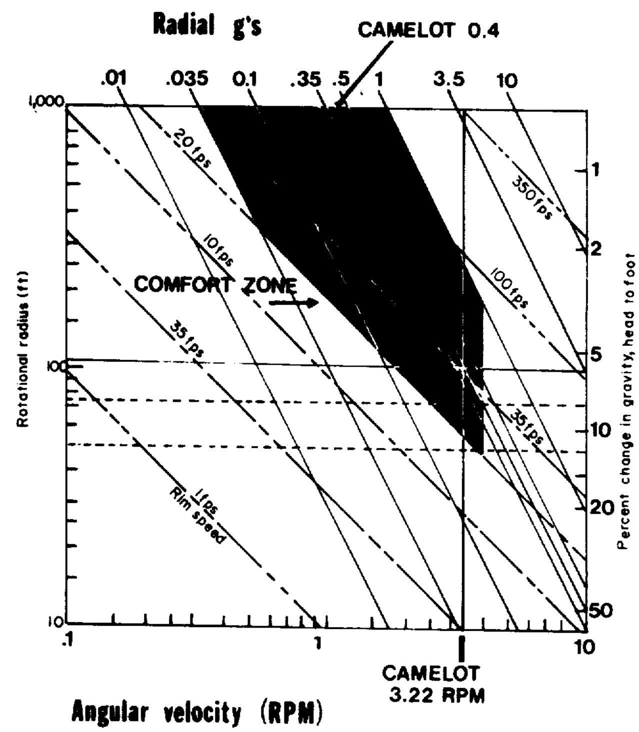
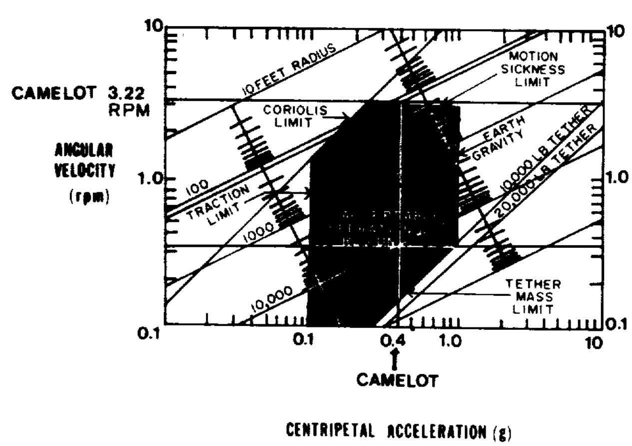
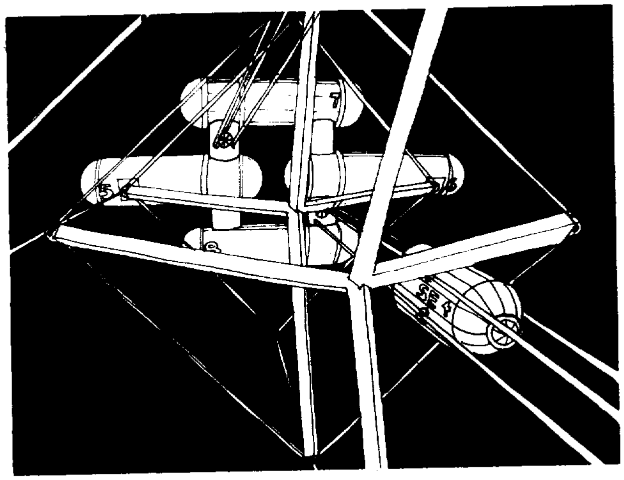


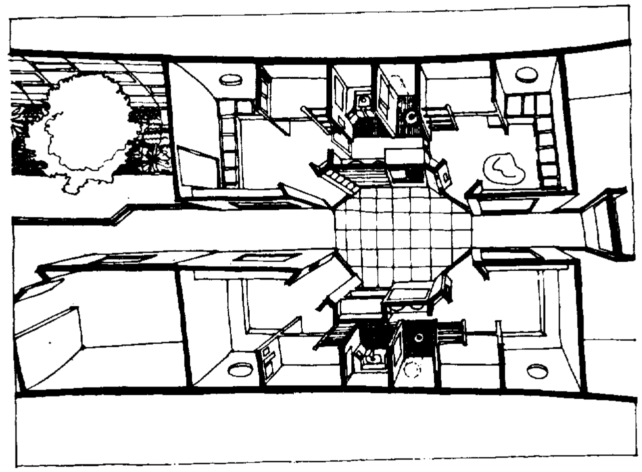
Rotational Parameters and Comfort Zone



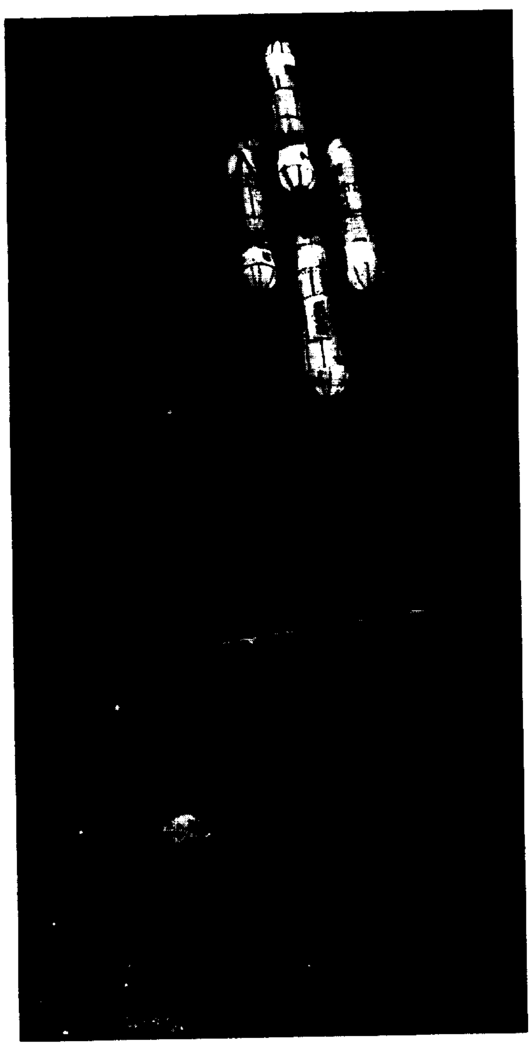
Artificial Gravity Parameters



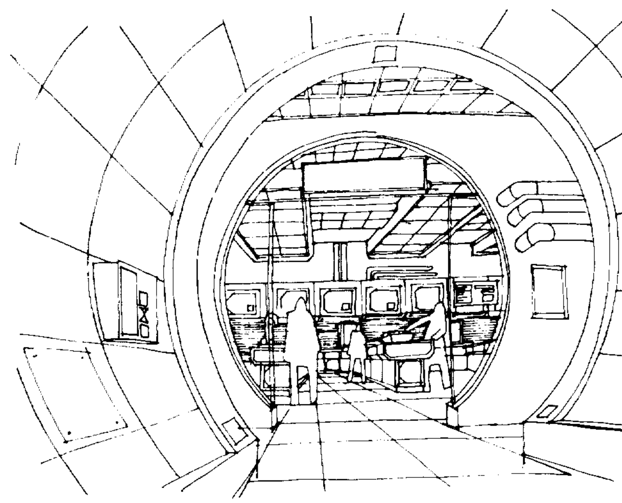
Camelot IV



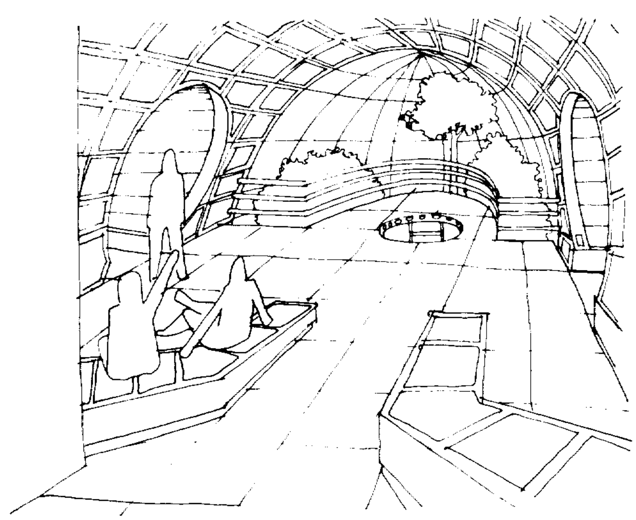
Dwelling Area Floor Plan



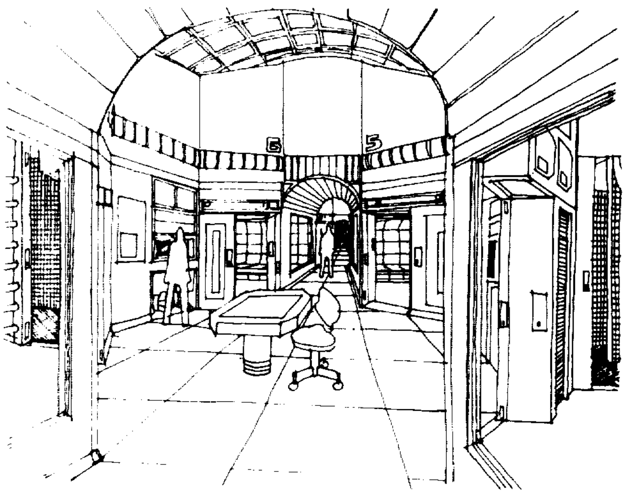
ET Array on Tether End



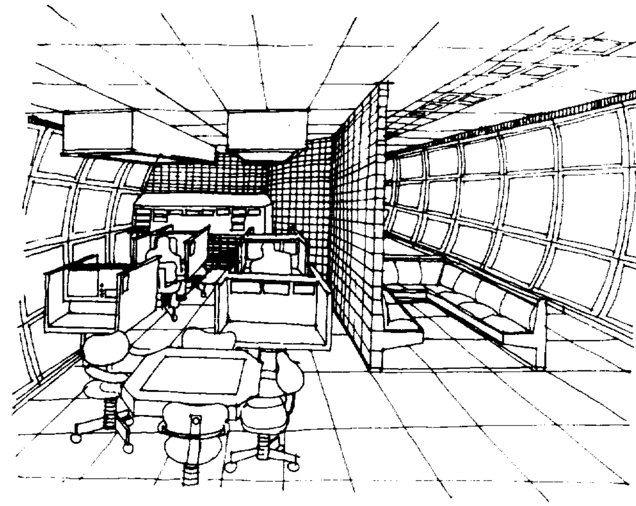
Master CELSS



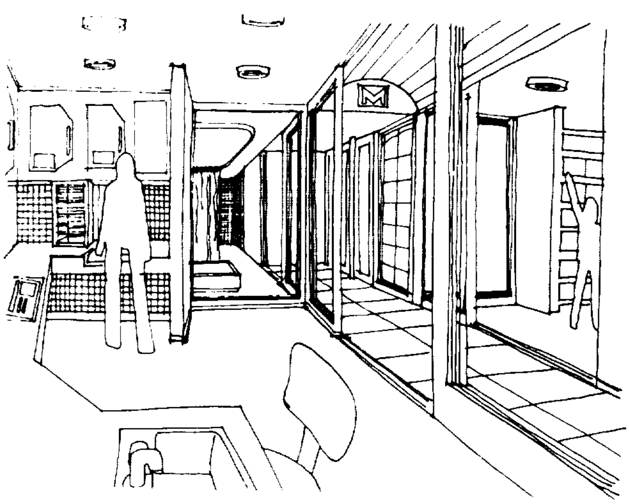
Meeting Area



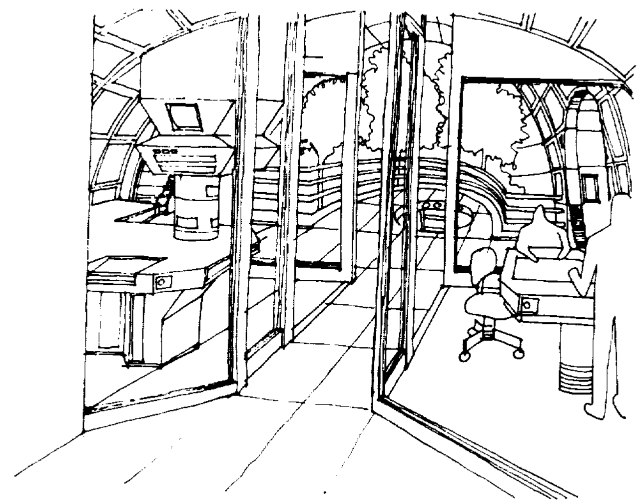
Dwelling Sector



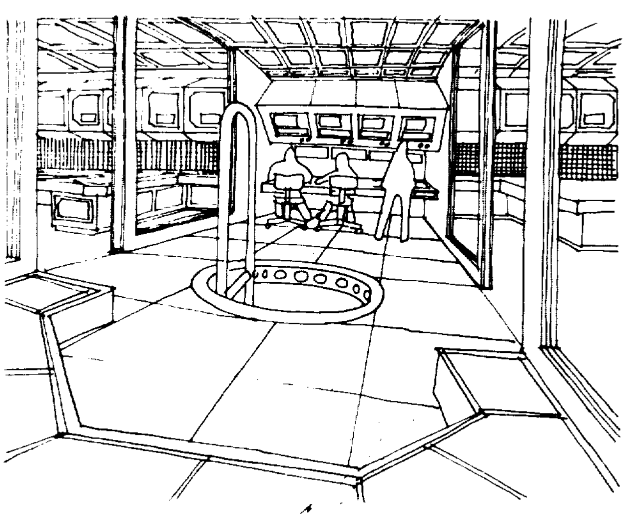
Library



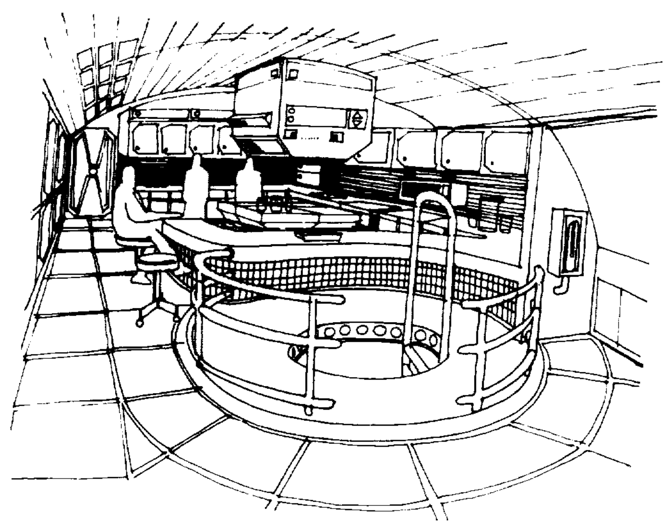
Laboratories



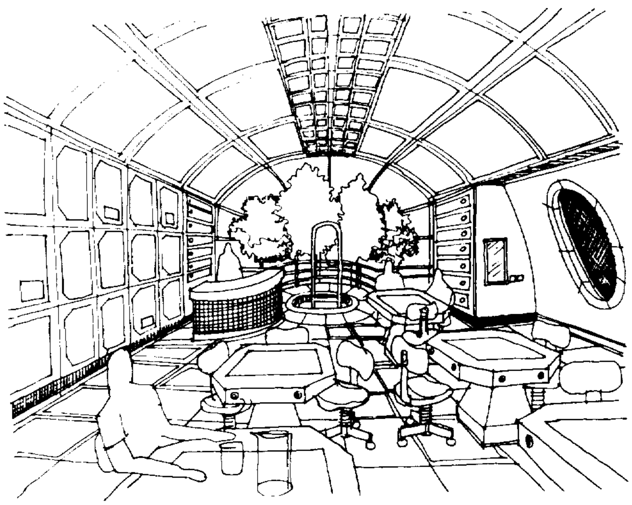
ET Control System



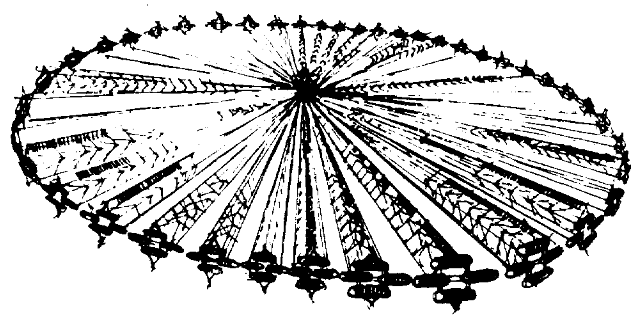
Lab Control Area



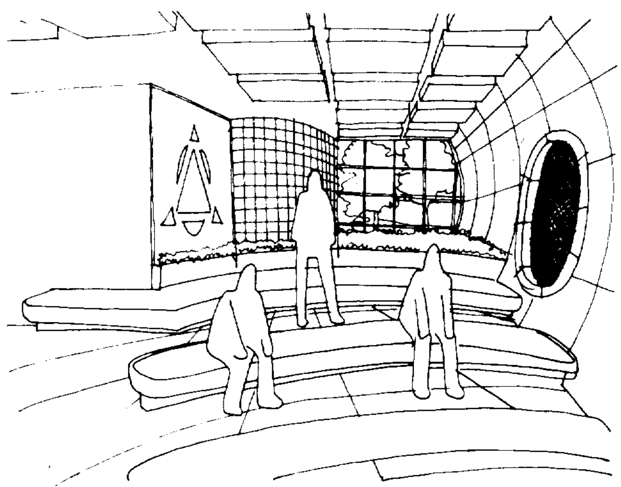
Galley



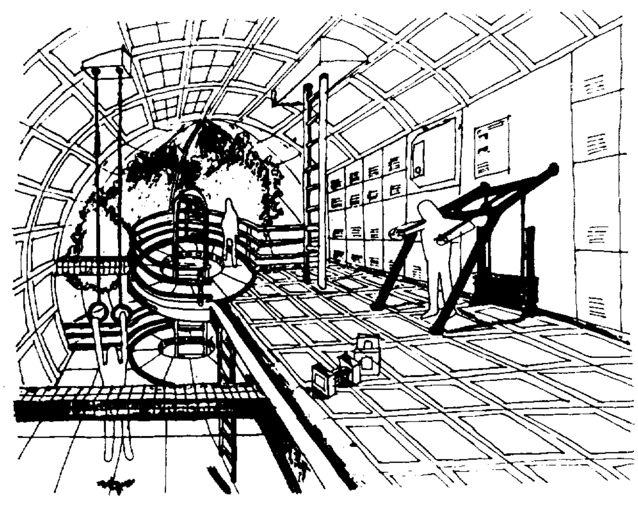
Dining-Conference Room



The Final Camelot



Chapel



Gym